2018

Three-fluid Heat Exchanger as Evaporator in Multi-source Heat Pumps with Viable Options for Alternative Defrosting Methods

Thore Oltersdorf
Fraunhofer ISE, Germany, thore.oltersdorf@ise.fraunhofer.de

Gerhard Schmitz
Technical University Hamburg Harburg, schmitz@tu-harburg.de

Hans-Martin Henning
Fraunhofer ISE, Germany, Hans-Martin.Henning@ise.fraunhofer.de

Three-fluid Heat Exchanger as Evaporator in Multi-source Heat Pumps with Viable Options for Alternative Defrosting Methods

Thore Oltersdorf[1]*, Gerhard Schmitz[2], Hans-Martin Henning[1]

[1] Fraunhofer Institute for Solar Energy Systems ISE,
Freiburg, Baden-Wurttemberg, Germany
Contact Information (+49 761 4588 5239, +49 761 4588 9239, toltersd@ise.fhg.de, henning@ise.fhg.de)

[2]Hamburg University of Technology, Institute of Engineering Thermodynamics,
Hamburg, Germany
Phone +49 (0)40 42878-3144, Fax +49 (0)40 42878-2967, schmitz@tuhh.de

* Corresponding Author

ABSTRACT

Three-fluid evaporators can be used for multi-source heat pumps to keep refrigeration circuits simple in design since it avoids the usage of a second or more evaporators. In this work a defrosting control design is presented with a lowered electrical energy demand compared to the standard procedure of reverse cycle defrosting with 4-way-valves. Objective of this new defrosting concept is to develop a fully autonomous defrosting strategy. The two heat sources allow direct thermal communication of an air source and a second heat source based on a hydronic circuit with the evaporating refrigerant. The proposed defrosting strategy is based on the combination of natural circulation defrosting and a hybrid defrosting strategy which allows defrosting during operation but at the expense of significantly higher heat source inlet temperatures above 0 °C of the hydronic-based heat source. The nominal operation and heat transfer from ambient air will be stopped thus the evaporation temperature can be increased up to defrosting temperature levels. Finally the two concepts of the de-facto standard reverse cycle defrosting and this new hybrid defrosting strategy are compared in their economic efficiency when designed for a single heat pumps.

1. INTRODUCTION

Air-to-water heat pumps are operated during the heating period usually under ambient conditions with frost accumulation on the heat transferring surfaces of the evaporator. Once criteria for performance degradations are detected or a threshold value is reached during operation the heat pump switches to the defrosting mode. For this mode 4-way reversing valves are installed as the de-facto standard defrosting technique to operate heat pump in a reverse mode.

Heat distribution systems in Germany are mainly based on hydronic circuits. The cooling mode operation of heat pumps with these valves is often equipped but still not a standardized feature. In case a heat pump is operated as an air conditioner such a system is either very limited in its cooling capacity to avoid passing below the wet bulb temperature at the surfaces of installed thermal distribution systems or additional investments in adequate devices is necessary that can handle this mode of operation including the formation of condensate water.

The performance loss by reverse-cycle defrosting and the limited use of heat pumps for air-conditioning opens up the possibility to develop alternative and/or improved defrosting techniques.

2. EVALUATION OF THE REFERENCE DEFROSTING TECHNIQUE

For evaluating the newly developed hybrid defrosting technique the reference defrosting technique needs to be quantified. Therefor the energy demand and any drawbacks of 4-way reversing valves need to be understood. Next to the direct and indirect energy demand – directly due to defrosting operation and indirect by compensating the

reverse operation by heating up thermal masses again – there are unavoidable penalties like leakage mass flows, thermal conduction phenomena between the connected lines, and a higher pressure drop within these lines.
Several attempts were done in the past to evaluate this defrosting method and other types of defrosting technologies for heat pumps. One of the most comprehensive investigations for the investigation and improvement of defrosting techniques applied by air-to-water heat pumps was done by Hubacher and Ehrbar (2000), Bertsch and Ehrbar (2002), and Ehrbar *et al.* (2006) in subsequent projects.
Bertsch and Ehrbar (2002) exhaustively analyzed these penalties and developed several approaches to quantify these penalties. One approach compares the share of electrical energy demand to a reference electrical energy which was fixed at 100 kWh, see Figure 1. Due to the nature of frost formation the highest share of energy demands for defrosting is caused by ambient conditions with relatively high loads of water which is the case for temperatures above 0 °C. It can be seen that these ambient conditions are the dominant effect. Even though the temperature lift increases from 42 K to 57 K there is almost no change in energy demand for defrosting.

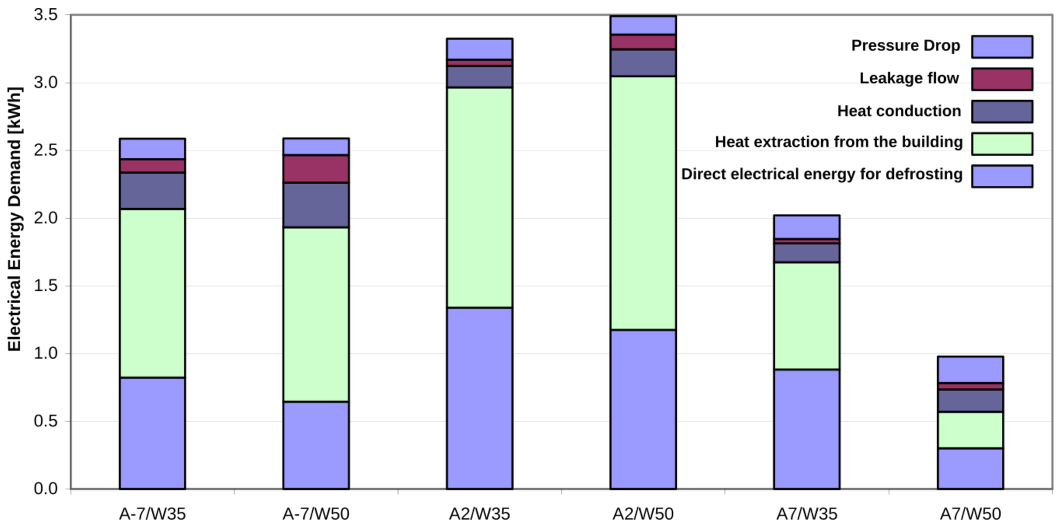


Figure 1: Electrical energy demand at typical working points for defrosting with reverse cycle defrosting to produce 100 kWh useful heat Bertsch and Ehrbar (2002).

This investigation of reverse cycle defrosting was performed with units tested at the heat pump laboratory of the University of Applied Sciences Buchs, Switzerland. In this work it will be investigated if this approach to determine the overall defrosting energy demand can be used to quantify defrosting energy demands in heat pump units operated under real-world field test conditions.

2.1 Evaluation of Reverse Cycle Defrosting in Real-World Field Tests

Field test data sets are analyzed to identify the share of electrical energy demand for defrosting. These data sets are based on a large-scale monitoring heat pump projects in Germany, see Miara et al. (2013). The used monitoring equipment investigates the heat pumps as black boxes. The data acquisition took place at a sample rate of 1 min. This is very close to typical defrosting times and an algorithm was developed and tested to combine the defrost energy calculation and the detection of false Positives in the result. By this procedure from field test locations more than 20 were equipped with air-to-water heat pumps from which only seven locations were identified with qualified data sets for defrosting evaluation. From these data sets a single location is selected.
For the monitoring sensor equipment there are only interfaces to the heat sink and the heat source. No data are acquired from the refrigerant circuit itself. For this reason correlations for losses like leakage flows, pressure drop and thermal conduction as defined in Bertsch and Ehrbar (2002) cannot be used.
Thus an investigation approach was applied as already done in Oltersdorf *et al.* (2013). Only measures were realized (a) to identify the direct electrical energy used for defrosting and (b) the heat extraction as indirect electrical energy consumption. With this approach a large share of the electrical energy demand can be quantified. But the other losses still add up substantially as seen in Figure 1 and need to be taken into account.
In this work an analysis of all these losses was included. The data from Figure 1 were used to create relationships between parameters which are available in the field test data sets with findings from these studies. Therefor the data

for specific working points in Figure 1 need to be correlated with parameters available in the monitoring data sets for each location.

For the leakage flow as well as the heat conduction the pressure difference between discharge and suction line is calculated by supply temperatures given in the monitoring data for the heat source and the heat sink. To identify the refrigerant pressure difference for the air-to-water heat pump constant pinch points of about 2 K for a plate heat exchanger as condenser and 7 K for a fin-and-tube heat exchanger as evaporator are assumed. For superheating it is assumed to operate with 10 K. Subcooling at the condenser outlet is considered to be 0 K. The pressure drop is considered to be constant. The resulting parameter sets for heat conduction and leakage flow were generated by linear regressions for the curves presented in Figure 2. To identify the absolute value of electrical energy demand these shares related to 100 kWh of useful heat needs to be correlated to the thermal energy produced between each period of normal operation before the next defrosting cycle will start.

The local peaks are generated due to the coincidence of relatively large temperature gradients between discharge and suction gas temperature as well as decreasing volume flows

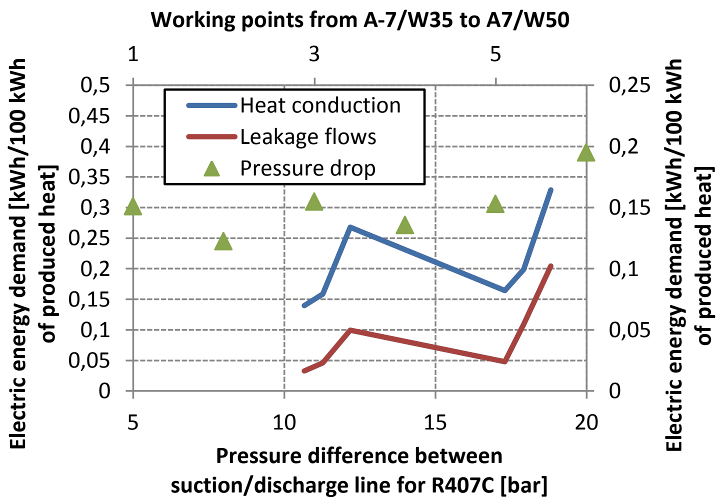


Figure 2: Correlations developed by analyzing the electrical energy demand for defrosting as given in Figure 1.

Depending on the ambient temperature each loss accounts for an additional electrical energy demand. In Figure 2 this is shown by the defrosting energy demand ratios (DED) with (dark green) and without losses (pale green). In red the constant values for the mean DED are indicated, see Equation 1 for the definition of this ratio.

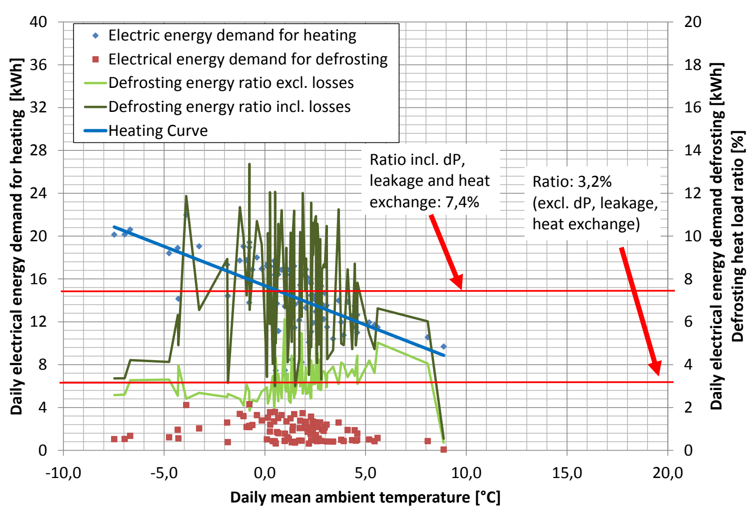


Figure 3: Field test object with different heat loads, defrosting behavior as well as energy demands for defrosting

2.2 Results

One field test location was investigated. Table 2 represents the mean defrosting energy demand ratios with (DED_1) and without losses (DED_2) due to operating the 4-way valve. The ratio is defined as

$$DED = \frac{kWh_{el}\ for\ defrosting\ (with\ or\ without)\ losses}{kWh_{el}\ for\ nominal\ heat\ pump\ operation}. \tag{1}$$

Table 1: Data from the investigated field test location.

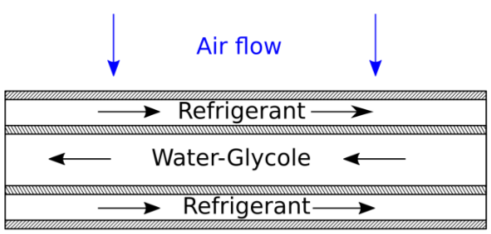
DED_1 [%]	DED_2 [%]	Operation Time [h]	Electrical energy demand for defrosting with reversing valve (all losses) [kWh]	Electrical energy demand for reheating due to defrosting periods [kWh]	Electrical energy demand heat pump [kWh]
3,2	7,4	3450	99,2	51,1	1341

Taking into account the additional losses it results into obvious changes of the electrical energy demand for reverse cycle defrosting. The DED ratios as well as the operation times will be used later in this study for an economic analysis of the presented defrosting strategies.

3. ALTERNATIVE DEFROSTING APPROACHES

3.1 System Design including the Defrosting Concept

A heat pump system design for the usage of two heat sources was developed, see Figure 3. The main idea is to introduce a three-fluid evaporator as a substitute of a conventional fin-and-tube evaporator to allow a cost-efficient integration of a secondary heat source on a small scale. Depending on the quality of the operation control of the heat pump as well as using a well-sized three-fluid heat exchanger the system's efficiency would improve by increasing the heat source temperature level, see Oltersdorf *et al.* (2011a) for more details on possible system concepts for heat pumps. In this study only aspects are investigated that are related to the defrosting techniques and its control.



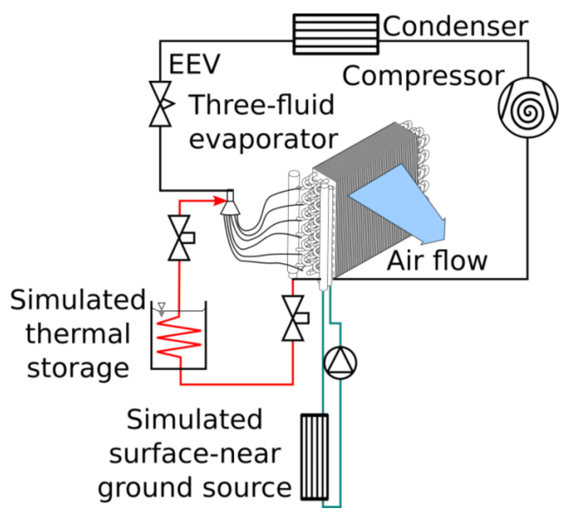


Figure 4: Left: Scheme of the principle of the used three-fluid-evaporator.
Right: Heat pump unit for two heat sources based on the usage of this three-fluid evaporator. The hydronic heat source is connected at the bottom of the scheme on the right side drawn in blue hydronic lines. The circuit connected in red lines shows the natural circulation two-phase thermosiphon which only operates during defrosting.

Two defrosting strategies are combined for the heat pump's defrosting. A natural circulation defrosting based on a two-phase thermosiphon is applied and secondly the specific evaporator design from Figure 4 allows a hybrid defrosting technique which allows a continuous heat pump operation and defrosting in parallel under condition that the hydronic-based heat source can deliver supply temperatures above 0 °C.

3.2 Natural Circulation Defrosting Techniques

The usage of an alternative defrosting approach needs a strategy to be developed that allows a fully autonomous operation. A non-autonomous approach would need backup strategies and probably additional devices which will increase costs. One approach for such an autonomous defrosting could be natural circulation defrosting as shown in Figure 3. The working principle of the natural circulation is the same as for two-phase thermosiphon loop. The successful operation of these devices is very sensitive for charging, which is the main challenge to develop a robust and autonomous defrosting strategy.
Former activities to use natural circulation defrosting in heat pumps based on the approach to have the normal refrigerant circuit cycle as a loop available during shutdown times of the heat pump, see Mildenberger (2008). The idea to use the same circuitry for the loop thermosiphon is simple and promising at first sight and seems to be easy to realize it only by bypassing EEV and compressor. The sensitivity for charging a thermosiphon loop makes this approach insensitive and does not lead to optimal operational behavior.
For this reason an additional minimal circuit is designed to have a short distance to the evaporator. The proposed design has a spiral heat exchanger and sufficient insulation to force the flow of the thermosiphon loop into a predestined direction.
In Figure 3 this should be the same direction as the nominal flow of refrigerant. The red lines are connected either with a tee-fitting upstream of the distributor or a distributor including a hot gas bypass connector can be used. Solenoid valves separate the loop circuit from the rest of the system. In defrosting operation the compressor and the EEV will limit the thermosiphon and the solenoid valves are normally open. In case of switching back to nominal operation the solenoid valves are closed. But one needs also to take into account influences by oil to operate such a thermosiphon in a sustainable manner. Therefor a control strategy before switching fully back to nominal operation is possible.
Charging is still a challenging task for natural circulation design but a geodesic design approach would be advantageous to use liquid refrigerant when opening up the EEV from the liquid receiver (not shown).
By analyzing the results from former testing campaigns the range of acceptable cooling capacities and charges can be correlated to each other. See Figure 4 and for a detailed description of these activities, see Oltersdorf *et al.* (2011b) or Höhlein (2011). Results for smaller charges than 550 g are not taken into account since the reached cooling capacities were too small for acceptable defrosting times and the operation can become unstable. By setting a lower limit of the temperature spread to at least 30 K and by applying charges of above 550 g a cooling capacity of at least 250 W can be reached. Estimating the remaining liquid share of refrigerant in the segments that participate in the thermosiphon loop is easy. This strategy simplifies the charging strategy for the thermosiphon's operation, too.

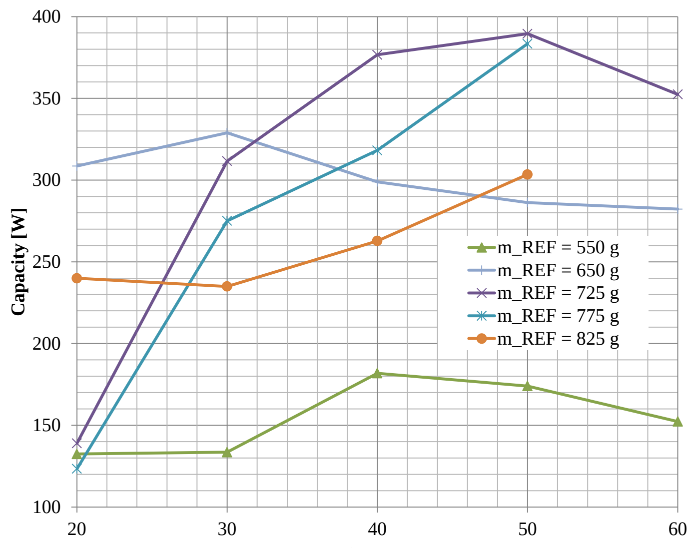


Figure 5: Performance of the natural circulation defrosting device

3.3 Three-Fluid Evaporator Defrosting Techniques

Besides this first defrosting technique a specific type of heat exchanger was investigated in which three fluids – one refrigerant and two heat source media communicate with each other. When two heat sources are installed and the hydronic-based heat source is able to heat up substantially above 0 °C it unlocks the usage of another defrosting technique. Air as the heat source can be switched off even though the operation of the heat pump continues. Figure 5 represents this strategy for a continuous defrosting, see also Oltersdorf *et al.* (2011b) or Tschiskale (2012). When the evaporator is frosted and frost detection takes place the water-glycol circuit is switched on and is controlled to operate with 15 °C. This represents and simulates the usage of a low-temperature solar thermal collector. It needs to be mentioned that the defrosting is far from being well operated. The switch of the heat sources took place manually. The EEV is fixed temporarily to have a constant superheat and to simulate continuous operation with the same conditions. As soon as the heat source starts to be regenerated the superheat control is switched on again. Overall the defrosting times in this exemplary campaign are about 12 min.

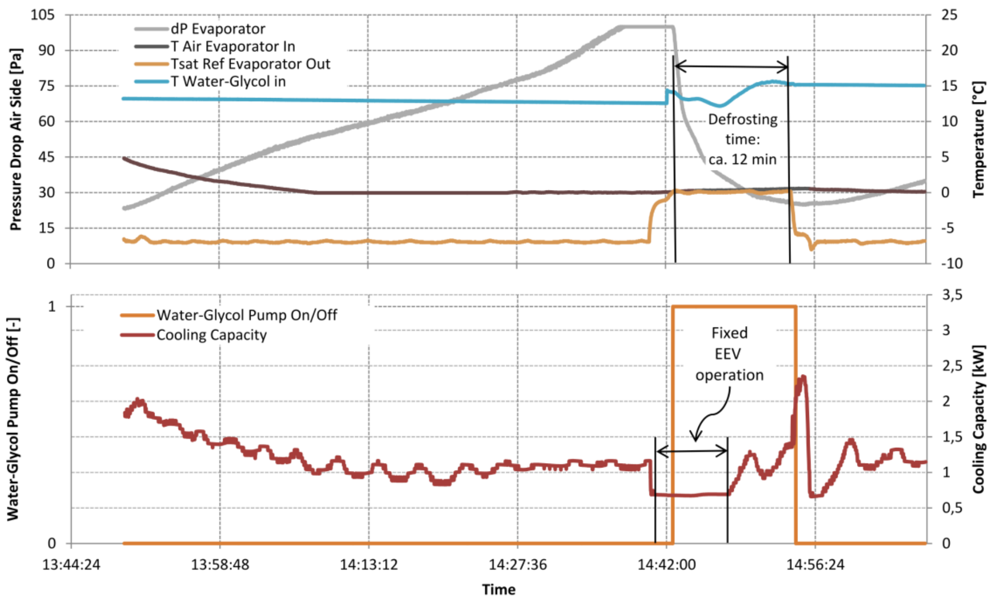


Figure 6: Three-fluid evaporator defrosting by operating the hydronic-based heat source and switch off the air-based heat source.

This defrosting technique demands for ambient temperatures of more than 0 °C. For this reason this technique can only represent a part of an autonomous defrosting strategy. The different capacities are determined by balancing the water-glycol as well as the refrigerant mass flow. The hydronic circuit reached 0,95 kW capacity and the cooling capacity is determined with 0,68 kW within the time period of 5 min started at 14:42. This time period does not reflect a typical defrosting period of a heat pump since the experiment was defined as a proof-of-concept.

3.4 Approach for an autonomous defrosting concept

Two defrosting techniques are presented above. From these two concepts only the natural circulation defrosting can be considered as an autonomous defrosting technique that does not need by default additional backups to ensure defrosting capabilities within a heat pump. Nevertheless due to the needed charging process to operate the natural circulation it would be beneficial to use it as a backup for other defrosting techniques. In this study it was combined with the defrosting by using the three-fluid evaporator. The second heat source used within the three-fluid evaporator was simulated as a solar thermal heat source. Like natural ventilation which uses the sensitive and latent heat of humid air, it is also a technique for defrosting only working at temperatures above 0 °C, see Bertsch and Ehrbar (2002) for details.

Figure 7 shows this combined concept on the right side compared to a conventional reverse-cycle defrosting on the left side. As long as the hydronic heat source of the heat pump allows the operation above 0 °C it will be the preferred defrosting strategy.

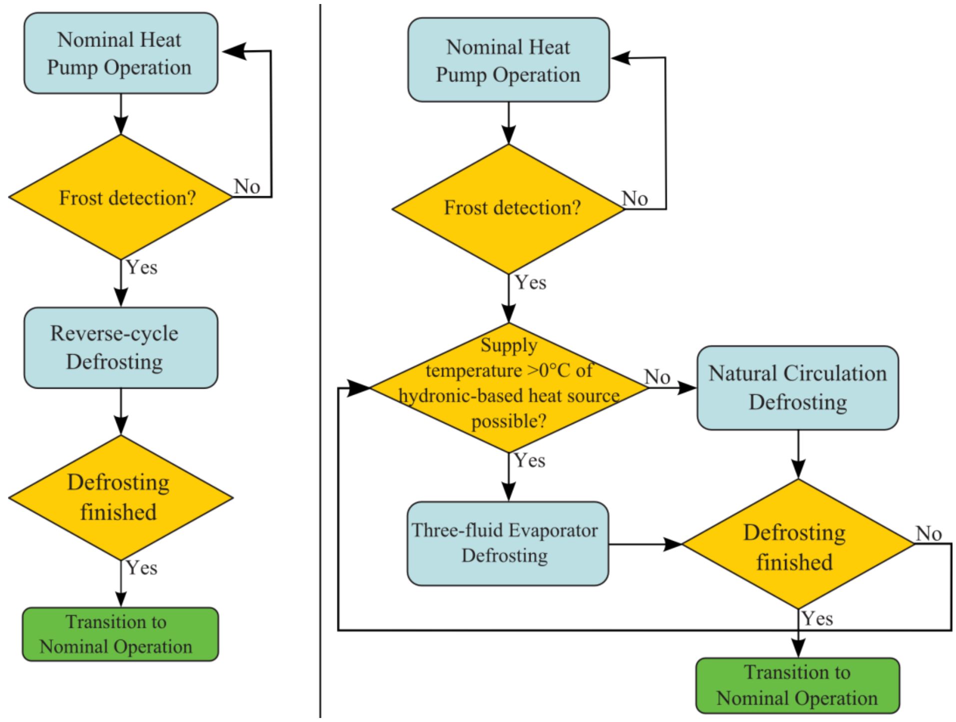


Figure 7: Left: Comparison of the conventional defrosting strategy with 4-way reverse valve. Right: proposed alternative defrosting approach combining three defrosting approaches.

4. ECONOMIC ANALYSIS

To identify the economic potential of such a defrosting strategy it is necessary to quantify the energy consumers and the total energy savings that are possible for each defrosting technique or its combination.
For the natural circulation defrosting the only permanent consumers are the solenoid valves. Typical valves used in refrigeration have a power consumption of about 15 W but solenoid valves are also available with the same functionality and less than 2 W power consumption. The power consumption for these two types of valves is calculated by the operation time of each heat pump as given in Table 2. Since there is no other function for these valves the consumed electrical energy needs to be considered fully as energy demand for the defrosting.
In analogy of the reverse cycle defrosting the natural circulation takes thermal energy for defrosting from the thermal masses or the heating system. This results indirectly into additional electrical power consumption to compensate for this heat extraction.
The evaluation of the power consumption for the defrosting with the three-fluid evaporator is more complex and it is crucial to define the system boundaries which consumers need to be considered as part of the defrosting concept. This type of evaporator is mainly designed and installed to be used as a second heat source. During normal operation it is used solely as heat source. It allows either higher cooling capacities or an optimized heat source management for the heat pump process. Thus all power consumptions of pumps, controls and valves either could be divided into different operation types (nominal and defrost operation) or could be neglected for the defrosting. In this study the latter approach was selected.
Depending on the applied types of solenoid valves the demand for electrical energy can be relatively large. The heat pump of the investigated field test object would need 51,8 kWh p.a. for the conventional valve and 6,9 kWh p.a. for the energy-saving device. With the electrical energy needed for reheating the house after defrosting cycles this adds up to the total electrical energy demand for natural circulation defrosting. Now the price per kWh for Germany for heat pumps of about 21,65 €-Ct. can be used to calculate energy costs, see Monitoring Report of the Federal Net Agency (2017). These data are given in Table 2.

Table 2: Comparison of energy costs the difference defrosting techniques

	Conventional valve			Energy-saving valve		
Price for Reverse-cycle defrosting [€]	Total energy demand by NCD [kWh]	Price [€]	Difference[€]	Total energy demand by NCD [kWh]	Price [€]	Difference[€]
32,5	102,9	22,3	10,3	56,6	12,2	20,3

In Table 3 the price estimations for the installation of the two defrosting concepts are listed. The prices for brazing points were calculated based on mass-specific prices for the brazing material itself. The price for a 4-way reverse cycle valve for defrosting was considered to be 77 € per unit according to Spahn (2018).

Table 3: Component list with unit prices based on results found at common refrigeration wholesalers and platforms

Natural Circulation Defrosting						
Component	**Specifications**	**Amount/Size**		**Price per piece**		**Total**
Copper tubes	6x1	6	m	4	€/m	24 €
Tee-Fitting	10x6x10	2	Units	1,5	€	3 €
Solenoid valve	10x10	2	Units	13	€	26 €
Brazing solder	CuP 281a	14	Braze points	0,16	€/g	0,39 €
Manufacturing		1	h	105	€/h	105 €
					Total	**158,4 €**
Three-fluid evaporator						
Fin-and-tube hex blank (4**R**12**TPR**, no bends, 7 fpi/plain)	10x1	1	Unit	150	€	150 €
Manifolds	22x1, 20x1, 10x1	0,3	m	6	€/m	1,8 €
Inner tubes mounted coaxial	6x0.5	17	m	4	€/m	68 €
Fittings (bends)	6x1, 10x1	84	Units	0,4	€	33,6 €
Brazing solder	CuP 281a	300	Braze points	0,16	€/g	4,94 €
Manufacturing		10	h	105	€/h	1050 €
					Total	**1308,3 €**

With this price information a pay-off time can be calculated which is listed in Table 4.

Table 4: Pay-off times in years for the compared defrosting techniques

NC + CV	TFED + CV	NC + TFED + CV	NC + ESSV	TFED + ESSV	NC + TFED + ESSV
15,4	127,4	142,8	7,8	64,5	72,3

In terms of the life-cycle of a system the pay-off times are reasonable in case of the application of an energy-saving solenoid valve. In case of using a conventional solenoid valve the pay-off is very close to the life-cycle of a heat pump and thus is not affordable. In case of the three-fluid evaporator there will no possibility to opt for this technology based on these results. The investments would never be economically affordable based on the single unit prices applied. The increase in lot sized can reduce manufacturing costs for both component lists. The additional use cases to build up a multiple source heat pump needs to be taken into account.

5. CONCLUSIONS

- Data from heat pump field test objects were analyzed to identify defrosting figures. This was realized for a single location. The electrical energy demand for defrosting was identified as 7.4% of the total electrical energy demand for heat pump operation when all losses are taken into account.
- Two defrosting techniques were presented with promising reduction in electrical energy demand from which the natural circulation defrosting reached about 130 W to almost 400 W whereas the hybrid defrosting with a three-fluid evaporator can be operated at similar ranges in defrosting capacities.
- An autonomous defrosting strategy as an alternative to reverse-cycle defrosting is presented.
- The technique of natural circulation defrosting would pay-off in a time scale of <8 years for energy-saving solenoid valves and close to the life-cycle of a heat pump when conventional solenoid valves are used.
- A three-fluid evaporator would not pay-off solely based on considering the benefits for defrosting.

NOMENCLATURE

CV	Conventional Solenoid Valve	
DED	Defrost Energy Demand Ratio	(kWh defrosting / TEED)
DED1	DED without additional valve losses	
DED2	DED with valve losses	
EEV	Electronic Expansion Valve	
ESSV	Energy-saving Solenoid Valve	
fpi	fins per inch	
NC	Natural Circulation	
p.a.	per annum	
TEED	Total Electrical Energy Demand	(kWh)
TFED	Three-fluid Evaporator Defrosting	
*XX***R***YY***TPR**	*XX* rows with *YY* tubes per row	

REFERENCES

Bertsch, B., Ehrbar, M. (2002). *Verbesserung des Abtauens bei luftbeaufschlagten Verdampfern. Phase 2: Bewertung der Abtauprozesse*. Innerstaatliche Hochschule für Technik, Buchs, Labor für Thermodynamik und Kältetechnik. Project No. 220187, Schweiz: BFE.

Ehrbar, M., Bertsch, S., Schwendener, S., Hubacher, P., & Bernal, C. (2006). *Verbesserung des Abtauens bei luftbeaufschlagten Verdampfern. Phase 3: technische Umsetzung, Labor- und Feldversuche*. Innerstaatliche Hochschule für Technik, Buchs, Labor für Thermodynamik und Kältetechnik. Project No. 250092, Schweiz: BFE.

Federal Network Agency and Federal Cartel Authority (2017). Monitoring Report 2017 (p. 9).

Höhlein, S. (2011), Charakterisierung eines Lamellen-Rundrohrwärmeübertragers für luftbeaufschlagte Wärmepumpen, HTWG Konstanz, Bachelor Thesis

Hubacher, B., Ehrbar, M. (2000). *Verbesserung des Abtauens bei luftbeaufschlagten Verdampfern. Phase 1: Analyse gängiger Abtauverfahren*. Innerstaatliche Hochschule für Technik, Buchs, Labor für Thermodynamik und Kältetechnik. Project No. 200133, Schweiz: BFE.

Miara, M., Günther, D., Langner, R., Helmling, S., & Wapler, J. (2013). *„WP Monitor“ - Feldmessung von Wärmepumpenanlagen*. Fraunhofer -Institut für Solare Energiesysteme ISE, Freiburg. BMWi, FKZ 0327401A, Germany. Final report available at https://wp-monitoring.ise.fraunhofer.de/wp-monitor-plus/download/endbericht_wp_monitor_klein.pdf, last accessed 30th April 2018.

Mildenberger, J. (2008). Aufbau eines Prüfstandes zur Untersuchung der Vereisungsproblematik einer CO_2-Luft/Wasser-Wärmepumpe mit Naturumlaufabtauung. Diplomarbeit. Braunschweig, Germany.

Oltersdorf, T., Oliva, A., & Henning, H.-M. (2011a). Experimentelle Untersuchung eines Direktverdampfers für solar unterstützte Luft/Wasser-Wärmepumpen kleiner Leistung mit zwei Wärmequellen. *In Proceedings of 21st Symposium Thermal Solar Energy. Kloster Banz, Germany* (ID 067). Regensburg, Germany: Otti e.V.

Oltersdorf, T., Hoehlein, S., Wapler, J., & Henning, H.-M. (2011b). Natural circulation defrosting in fin-and-tube heat exchangers with highly distributed refrigerant mass flow. 10th IEA Heat Pump Conference. Paper #162. Tokyo, Japan: IEA HP Program

Oltersdorf, T., Langner, R., Miara, M., & Schmitz, G. (2013). Untersuchung der Abtauung von Verdampfern in WP-Feldtests und Laborversuchen. DKV Annual Meeting, Würzburg, Germany. Paper IV.15. Hannover, Germany: DKV

Spahn, H.-J. (2018). Personal communication.

Tschiskale, D. (2012), Experimentelle Untersuchungen und Vergleich eines luft- und flüssigkeitsbeaufschlagten Kombiverdampfers für Wärmepumpen, Ostfalia Hochschule für angewandte Wissenschaften, Bachelor Thesis